

(19) World Intellectual Property Organization  
International Bureau



(43) International Publication Date  
24 December 2008 (24.12.2008)

PCT

(10) International Publication Number  
**WO 2008/157510 A1**

- (51) International Patent Classification:  
*H01L 21/04* (2006.01) *H01L 29/15* (2006.01)
- (21) International Application Number:  
PCT/US2008/067149
- (22) International Filing Date: 16 June 2008 (16.06.2008)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:  
60/944,206 15 June 2007 (15.06.2007) US
- (71) Applicant (for all designated States except US): **THE REGENTS OF THE UNIVERSITY OF CALIFORNIA** [US/US]; 1111 Franklin Street, 12th Floor, Oakland, California 94607 (US).
- (72) Inventors; and
- (75) Inventors/Applicants (for US only): **HIRAI, Asako** [JP/US]; 114 Conejo Road, Santa Barbara, California 93103 (US). **JIA, Zhongyuan** [CN/US]; 769 Cypress Walk, Apt. E, Goleta, California 93117 (US). **SAITO,**

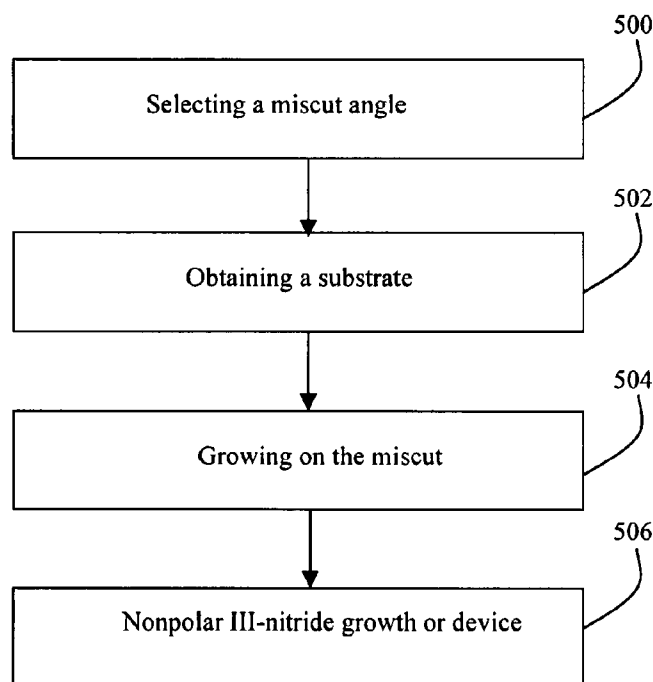
**Makoto** [JP/US]; 5094 Parkwood Place, Santa Barbara, California 93111 (US). **YAMADA, Hisashi** [JP/JP]; 2-13-10-102 Amakubo, Tsukuba 305-0005 (JP). **ISO, Kenji** [JP/JP]; 3-19-14-304 Hatori, Fujisawa, Kanagawa 251-0056 (JP). **DENBAARS, Steven P.** [US/US]; 283 Elderberry Drive, Goleta, California 93117 (US). **NAKA-MURA, Shuji** [US/US]; P.O. Box 61656, Santa Barbara, California 93160 (US). **SPECK, James S.** [US/US]; 947 West Campus Lane, Goleta, California 93117 (US).

(74) Agent: **GATES, George H.**; Gates & Cooper LLP, 6701 Center Drive West, Suite 1050, Los Angeles, California 90045 (US).

(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, SV,

[Continued on next page]

(54) Title: PLANAR NONPOLAR M-PLANE GROUP III NITRIDE FILMS GROWN ON MISCUT SUBSTRATES



(57) Abstract: A nonpolar III-nitride film grown on a miscut angle of a substrate, in order to suppress the surface undulations, is provided. The surface morphology of the film is improved with a miscut angle towards an  $\alpha$ -axis direction comprising a  $0.15^\circ$  or greater miscut angle towards the  $\alpha$ -axis direction and a less than  $30^\circ$  miscut angle towards the  $\alpha$ -axis direction.

Fig. 5



SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN,  
ZA, ZM, ZW.

NO, PL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG,  
CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

**(84) Designated States** (*unless otherwise indicated, for every  
kind of regional protection available*): ARIPO (BW, GH,  
GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM,  
ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM),  
European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI,  
FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MT, NL,

**Declaration under Rule 4.17:**

— *of inventorship (Rule 4.17(iv))*

**Published:**

— *with international search report*

PLANAR NONPOLAR m-PLANE GROUP III NITRIDE FILMS  
GROWN ON MISCUT SUBSTRATES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit under 35 U.S.C. Section 119(e) of co-pending and commonly-assigned U.S. Provisional Patent Application Serial No. 60/944,206, filed on June 15, 2007, by Asako Hirai, Zhongyuan Jia, Makoto Saito, Hisashi Yamada, Kenji Iso, Steven P. DenBaars, Shuji Nakamura, and James S. Speck, entitled "PLANAR NONPOLAR m-PLANE GROUP III NITRIDE FILMS GROWN ON MISCUT SUBSTRATES" attorneys' docket number 30794.238-US-P1 (2007-674), which application is incorporated by reference herein.

This application is related to the following co-pending and commonly-assigned U.S. patent applications:

U.S. Provisional Application Serial No. 60/954,770, filed on August 8, 2007, by Hisashi Yamada, Kenji Iso, and Shuji Nakamura, entitled "NONPOLAR III-NITRIDE LIGHT EMITTING DIODES WITH LONG WAVELENGTH EMISSION," attorney's docket number 30794.247-US-P1 (2008-063);

U.S. Provisional Application Serial No. 60/954,767, filed on August 8, 2007, by Hisashi Yamada, Kenji Iso, Makoto Saito, Asako Hirai, Steven P. DenBaars, James S. Speck, and Shuji Nakamura, entitled "III-NITRIDE FILMS GROWN ON MISCUT SUBSTRATES," attorney's docket number 30794.248 -US-P1 (2008-062); and

U.S. Provisional Application Serial No. 60/954,744, filed on August 8, 2007, by Kenji Iso, Hisashi Yamada, Makoto Saito, Asako Hirai, Steven P. DenBaars, James S. Speck, and Shuji Nakamura, entitled "PLANAR NONPOLAR M-PLANE GROUP III-NITRIDE FILMS GROWN ON MISCUT SUBSTRATES," attorney's docket number 30794.249 -US-P1 (2008-004);

which applications are incorporated by reference herein.

## BACKGROUND OF THE INVENTION

### 5           1.       Field of the Invention.

The present invention relates to a technique for the growth of planar films of nonpolar *m*-plane, and more specifically, to a technique for the growth of an atomically smooth *m*-GaN film without any surface undulations.

### 10           2.       Description of the Related Art.

The usefulness of gallium nitride (GaN) and its ternary and quaternary compounds incorporating aluminum and indium (AlGaN, InGaN, AlInGaN) has been well established for fabrication of visible and ultraviolet optoelectronic devices and high-power electronic devices. These compounds are referred to herein as Group III  
15   nitrides, or III-nitrides, or just nitrides, or by the nomenclature (Al,B,Ga,In)N. Devices made from these compounds are typically grown epitaxially using growth techniques including molecular beam epitaxy (MBE), metalorganic chemical vapor deposition (MOCVD), and hydride vapor phase epitaxy (HVPE).

GaN and its alloys are the most stable in the hexagonal würtzite crystal  
20   structure, in which the structure is described by two (or three) equivalent basal plane axes that are rotated 120° with respect to each other (the *a*-axis), all of which are perpendicular to a unique *c*-axis. Group III and nitrogen atoms occupy alternating *c*-planes along the crystal's *c*-axis. The symmetry elements included in the würtzite structure dictate that III-nitrides possess a bulk spontaneous polarization along this *c*-  
25   axis, and the würtzite structure exhibits piezoelectric polarization.

Current nitride technology for electronic and optoelectronic devices employs nitride films grown along the polar *c*-direction. However, conventional *c*-plane quantum well structures in III-nitride based optoelectronic and electronic devices suffer from the undesirable quantum-confined Stark effect (QCSE), due to the  
30   existence of strong piezoelectric and spontaneous polarizations. The strong built-in electric fields along the *c*-direction cause spatial separation of electrons and holes that

in turn give rise to restricted carrier recombination efficiency, reduced oscillator strength, and red-shifted emission.

One approach to eliminating the spontaneous and piezoelectric polarization effects in GaN optoelectronic devices is to grow the devices on nonpolar planes of the crystal. Such planes contain equal numbers of Ga and N atoms and are charge-neutral. Furthermore, subsequent nonpolar layers are equivalent to one another so the bulk crystal will not be polarized along the growth direction. Two such families of symmetry-equivalent nonpolar planes in GaN are the  $\{11\bar{2}0\}$  family, known collectively as *a*-planes, and the  $\{1\bar{1}00\}$  family, known collectively as *m*-planes.

The other cause of polarization is piezoelectric polarization. This occurs when the material experiences a compressive or tensile strain, as can occur when (Al, In, Ga, B)N layers of dissimilar composition (and therefore different lattice constants) are grown in a nitride heterostructure. For example, a thin AlGa<sub>x</sub>N<sub>1-x</sub> layer on a GaN template will have in-plane tensile strain, and a thin InGa<sub>x</sub>N<sub>1-x</sub> layer on a GaN template will have in-plane compressive strain, both due to lattice matching to the GaN. Therefore, for an InGa<sub>x</sub>N<sub>1-x</sub> quantum well on GaN, the piezoelectric polarization will point in the opposite direction than that of the spontaneous polarization of the InGa<sub>x</sub>N<sub>1-x</sub> and GaN. For an AlGa<sub>x</sub>N<sub>1-x</sub> layer latticed matched to GaN, the piezoelectric polarization will point in the same direction as that of the spontaneous polarization of the AlGa<sub>x</sub>N<sub>1-x</sub> and GaN.

The advantage of using nonpolar planes over *c*-plane nitrides is that the total polarization will be reduced. There may even be zero polarization for specific alloy compositions on specific planes. Such scenarios will be discussed in detail in future scientific papers. The important point is that the polarization will be reduced compared to that of *c*-plane nitride structures.

Although high performance optoelectronic devices on nonpolar *m*-plane GaN have been demonstrated, it is known to be difficult to obtain smooth surfaces for the *m*-plane non polar GaN. The *m*-plane GaN surface is typically covered with facets or rather macroscopic surface undulations. Surface undulation is mischievous, for

example, because it would originate faceting in quantum structures, and inhomogeneous incorporation of alloy atoms or dopants depend on the crystal facets, etc.

- 5           The present invention describes a technique for the growth of planar films of nonpolar *m*-plane nitrides. For example, an atomically smooth *m*-GaN film without any surface undulations has been demonstrated using this invention.

### SUMMARY OF THE INVENTION

- 10           The present invention discloses a method for growing planar nonpolar III-nitride films that have atomically smooth surfaces, without any macroscopic surface undulations, by selecting a miscut angle of a substrate upon which the nonpolar III-nitride films are grown, in order to suppress the surface undulations of the nonpolar III-nitride films. The miscut angle is an in-plane miscut angle towards the *a*-axis  
15           direction, wherein the miscut angle is a 0.15° or greater miscut angle towards the *a*-axis direction and a less than 30° miscut angle towards the *a*-axis direction.

- The present invention discloses a nonpolar III-nitride film growth on a miscut of a substrate, wherein a top surface of the film is a nonpolar plane and the miscut is a surface of the substrate angled at a miscut angle with respect to a crystallographic  
20           plane of the substrate.

- The miscut angle may be 0.15° or greater. The crystallographic plane may be an *m*-plane, the nonpolar III-nitride film may be *m*-plane, and the miscut angle may be towards an *a*-axis direction and comprise a 0.15° or greater miscut angle towards the *a*-axis direction and a less than 30° miscut angle towards the *a*-axis direction. The  
25           top surface may be atomically smooth or planar. The miscut angle may be such that a root mean square (RMS) step height of one or more undulations on the top surface, over a length of 1000 micrometers, is 50 nm or less. The miscut angle may be such that a maximum step height of the undulations on the top surface, over a length of 1000 micrometers is 61 nm or less. The undulations may comprise faceted pyramids.

The crystallographic plane may be a nonpolar plane. The miscut angle may be sufficiently small such that the film is nonpolar. The miscut angle may be such that the top surface, and one or more surfaces of one or more layers deposited on the top surface, are sufficiently smooth for a quantum well interface or a heterojunction interface.

The film may be a substrate or template and the top surface is suitable for subsequent growth of device-quality (Al,B,Ga,In)N layers on the top surface. A device may be fabricated using the film.

The present invention further discloses a method for growing a III-nitride, comprising growing a nonpolar III-nitride film on a miscut of a substrate, wherein the miscut comprises a surface of the substrate angled with a miscut angle with respect to a crystallographic plane of the substrate, in order to increase surface flatness of the nonpolar III-nitride film. The method may further comprise the step of selecting the miscut angle in order to suppress surface undulations of the nonpolar III-nitride film to achieve a smooth surface morphology of the film. The crystallographic plane may be an *m*-plane, the nonpolar III-nitride film may be *m*-plane, and the miscut angle may be towards an *a*-axis direction and comprise a  $0.15^\circ$  or greater miscut angle towards the *a*-axis direction and a less than  $30^\circ$  miscut angle towards the *a*-axis direction. A nonpolar III-nitride film may be fabricated using the method.

The present invention further discloses a nonpolar III-nitride-based device comprising a nonpolar III-nitride film, having a smooth surface morphology, grown on a miscut of a substrate.

## BRIEF DESCRIPTION OF THE DRAWINGS

Referring now to the drawings in which like reference numbers represent corresponding parts throughout:

Figs. 1(a) and 1(b) are schematic drawings of a cross-section of a GaN film along the *a*-axis direction on a freestanding *m*-GaN substrate with miscut angles.

Figs. 2(a), 2(b) and 2(c) are optical micrographs of the surface of an *m*-plane GaN film grown on a freestanding *m*-GaN substrate with various miscut angles, wherein Fig. 2(a) shows the surface of an *m*-plane GaN film grown on a freestanding *m*-GaN substrate with a miscut angle of 0.01°, Fig. 2(b) shows the surface of an *m*-plane GaN film grown on a freestanding *m*-GaN substrate with a miscut angle of 0.15°, and Fig. 2(c) the surface of an *m*-plane GaN film grown on a freestanding *m*-GaN substrate with a miscut angle of 0.30°.

Fig. 3 shows a root mean square (RMS) value evaluated from step height measurements of an *m*-plane GaN pyramid feature grown on a freestanding *m*-GaN substrate with various miscut angle variations.

Fig. 4 shows a maximum height value evaluated from step height measurements of an *m*-plane GaN film grown on a freestanding *m*-GaN substrate with various miscut angle variations.

Fig. 5 is a flowchart illustrating a method of the present invention.

Fig. 6 is a cross sectional schematic of a device according to the present invention.

## DETAILED DESCRIPTION OF THE INVENTION

In the following description of the preferred embodiment, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration a specific embodiment in which the invention may be practiced. It is to be understood that other embodiments may be utilized and structural changes may be made without departing from the scope of the present invention.

### Overview

One embodiment of the present invention describes a method of obtaining a smooth surface morphology for nonpolar III-nitride films. Specifically, surface undulations of nonpolar III-nitride films are suppressed by controlling the miscut angle of the substrate upon which the nonpolar III-nitride films are grown.



Current nitride devices are typically grown in the polar [0001] *c*-direction, which results in charge separation along the primary conduction direction in vertical devices. The resulting polarization fields are detrimental to the performance of  
5 current state of the art optoelectronic devices.

Growth of these devices along a nonpolar direction has improved device performance significantly by reducing built-in electric fields along the conduction direction. However, macroscopic surface undulations typically exist on their surfaces, which is harmful to successive film growth.

10 Until now, no means existed for growing nonpolar III-nitride films without macroscopic surface undulations, even though they provide better device layers, templates, or substrates for device growth. The novel feature of this invention is that nonpolar III-nitride films can be grown as macroscopically and atomically planar films via a miscut substrate. As evidence of this, the inventors have grown {10-10}  
15 planar films of GaN. However, the scope of this invention is not limited solely to these examples; instead, the present invention is relevant to all nonpolar planar films of nitrides, regardless of whether they are homoepitaxial or heteroepitaxial.

#### Technical Description

20 The present invention comprises a method of growing planar nonpolar III-nitride films utilizing miscut substrates in the growth process. For example, it is critically important that the substrate has a miscut angle in the proper direction for growth of both macroscopically and atomically planar {10-10} GaN.

In the present invention, a GaN film was grown using a conventional MOCVD  
25 method on a freestanding *m*-GaN substrate with a miscut angle along an *a*-axis direction. The thickness of the GaN was 5  $\mu\text{m}$ . The surface morphology was investigated by optical microscopy, Atomic Force Microscopy (AFM), and step height measurements.

Figs. 1(a) and 1(b) are schematic drawings of the cross-section of the GaN  
30 film along the *a*-axis direction on an *m*-plane miscut substrate. Specifically, Fig. 1(a)

is a schematic drawing of the cross-section of the GaN film 100 along the  $a$ -axis direction 102 on the surface 104 of an on-axis  $m$ -plane substrate, wherein pyramid facets 106a, 106b of the GaN film 100 form an isosceles triangle with an angle of  $\alpha$  on the substrate 104, and Fig. 1(b) is a schematic drawing of the cross-section of the GaN film 108 along the  $a$ -axis direction 102 on the surface 110 of a substrate with miscut angle of  $\theta$ , wherein pyramid facets 112a, 112b of the GaN film 108 with angles of  $\beta$  and  $\gamma$  on the surface 110 of the substrate. The  $m$ -plane 114 of the substrates in Figs. 1(a) and 1(b) is also shown.

The inventors confirmed the same facets independent of the miscut angles from AFM. Therefore,  $\theta$  is defined by following equations,

$$\beta = \alpha - \theta \quad \text{Eq. (1)}$$

$$\gamma = \alpha + \theta \quad \text{Eq. (2)}$$

$$\theta = (\beta - \alpha) / 2 \quad \text{Eq. (3)}$$

### Experimental Results

{10-10} GaN films grown on a substrate that is nominally on-axis has been found to have macroscopic surface undulations consisting of four-faceted pyramids. These pyramid facets are typically inclined to the  $a$ ,  $c^+$  and  $c^-$  directions, as shown in Figs. 2(a) and 2(b), wherein Fig. 2(a) has a miscut angle of  $0.01^\circ$  and Fig. 2(b) has a miscut angle of  $0.15^\circ$ . It was found that a smoother surface was obtained by increasing the miscut angle to  $0.15^\circ$ . It was also found that the surface on the substrate with a miscut angle of  $0.30^\circ$  has a smooth morphology, as shown in Fig. 2(c).

Fig. 3 shows the RMS values evaluated from step height measurements of  $m$ -plane GaN pyramid features grown on substrates with various miscut angles. The RMS values over  $1000 \mu\text{m}$  lengths of the films on the each miscut substrate were 183

nm, 121 nm, 47 nm, 7.3 nm, 13 nm, and 13 nm, for mis-orientation angles of  $0.01^\circ$ ,  $0.075^\circ$ ,  $0.15^\circ$ ,  $0.225^\circ$ ,  $0.30^\circ$ , and  $30^\circ$ , respectively. The RMS values were found to decrease with increasing miscut angles. In general, an RMS value less than 50 nm is  
 5 expected for optoelectronic and electronic devices. Thus, it is preferable that the miscut angle of the substrate be  $0.15^\circ$  or greater.

Fig. 4 shows the maximum step height values evaluated from step height measurements of *m*-plane GaN pyramid features grown on substrates with various miscut angles. The maximum step height values over 1000  $\mu\text{m}$  lengths of the films  
 10 on each miscut substrate were 974 nm, 427 nm, 61 nm, 14 nm, 13 nm, and 25 nm, for mis-orientation angles of  $0.01^\circ$ ,  $0.075^\circ$ ,  $0.15^\circ$ ,  $0.225^\circ$ ,  $0.30^\circ$ , and  $30^\circ$ , respectively. The maximum step height values were found to decrease with increasing miscut angles. Judging from Fig. 4, it is preferable that the miscut angle of the substrate be  $0.15^\circ$  or greater.

15

#### Process Steps

Fig. 5 is a flowchart illustrating a method (see also Fig. 1(a) and Fig. 1(b)) for growing III-nitride layers, comprising one or more of the following steps:

Block 500 represents the step of selecting a miscut angle  $\theta$  in order to suppress  
 20 surface undulations of the nonpolar III-nitride film.

Block 502 represents the step of obtaining a substrate having a miscut with the desired miscut angle. The miscut may be obtained by slicing the substrate, or selecting a substrate with the desired miscut, for example.

Block 504 represents the step of growing the nonpolar III-nitride layer on the  
 25 miscut of the substrate, wherein the miscut comprises a surface 110 of the substrate angled with the miscut angle  $\theta$  with respect to a crystallographic plane 114 of the substrate, in order to increase surface flatness of the nonpolar III-nitride film 108. The crystallographic plane 114 may be an *m*-plane, the nonpolar III-nitride film 108 may be *m*-plane, and the miscut angle  $\theta$  may be towards an *a*-axis direction and

comprise a  $0.15^\circ$  or greater miscut angle towards the a-axis direction and a less than  $30^\circ$  miscut angle towards the a-axis direction.

Block 506 represents a nonpolar III-nitride-based device or film grown using the method, comprising, for example, a nonpolar III-nitride film having a smooth surface morphology, grown on a miscut of a substrate, wherein the surface morphology is smoother than without the miscut.

Fig. 6 is a cross-sectional schematic of a nonpolar III-nitride film 600, e.g. a growth, on a miscut 602a of a substrate 604, wherein a top surface 606 of the film 600 is a nonpolar plane. The miscut 602a may be a surface 602b of the substrate 604 angled at a miscut angle 608 with respect to a crystallographic plane 610 of the substrate 604. The crystallographic plane 610 may be a nonpolar plane. The miscut angle 608 may be from any crystallographic plane 610, e.g. a semipolar plane or c-plane, such that the film 600 is nonpolar or has a nonpolar orientation.

The film 600 may be an m-plane III-nitride nonpolar film such as GaN, the crystallographic plane 610 may be m-plane, and the miscut angle 608 may be towards an a-axis direction 612 and comprise a  $0.15^\circ$  or greater miscut angle 608 towards the a-axis direction 612 and a less than  $30^\circ$  miscut angle 608 towards the a-axis direction 612. However the angular range for the miscut angle greater than  $0.15^\circ$  and less than  $30^\circ$  should also hold true for other nonpolar III-nitride material films 600 (e.g. a-plane or m-plane (Al,B,Ga,In)N compounds) and with miscuts in other nonpolar directions 612 and with respect to other nonpolar crystallographic planes 610. Therefore, the miscut angle 608 may be  $0.15^\circ$  or greater, and less than  $30^\circ$ , with respect to any crystallographic plane 610 or in any direction 612, so long as the miscut angle 608 achieves a nonpolar film 600, for example. For example, the miscut angle 608 may be sufficiently small such that the film 600 is nonpolar.

The film 600, or the top surface 606 of the film 600 may comprise surface undulations (116 in Fig. 1(b)), which may be suppressed by the miscut angle 608 (generally, increasing the miscut angle 608 increases suppression of the undulations 116, or increases smoothness and flatness, or reduces step height 118a of undulations

116). The surface undulations 116 may comprise faceted pyramids. The miscut angle 608 may be such that a root mean square (RMS) step height 118a of the one or more undulations 116 on the top surface 606, over a length of 1000 micrometers, is 50 nm or less. The miscut angle 608 may be such that a maximum step height 118a of the undulations 116 on the top surface 606, over a length of 1000 micrometers is 61 nm or less. The surface undulations 116 may be suppressed by the miscut angle 608 such that a step height 118a of the undulations 116 is less than the step height 118b of undulation(s) 120 without the miscut. The film 600 may comprise a top surface 606 which is atomically smooth, planar, flat, or faceted.

Surface undulations 200a and 200b are also shown in Figs. 2(a) and 2(b), respectively. In Fig. 2(b), the miscut angle  $\theta$  is increased so that the surface undulations 200b are suppressed as compared to surface undulations 200a. In Fig. 2(c), the miscut angle  $\theta$  is increased still further so that the surface undulations are suppressed even further or are non-existent.

The film 600 may further comprise III-nitride 614a deposited on the top surface 606. The miscut angle 608 may be such that the top surface 606, and/or surface(s) 614b of one or more layers 614a grown on the top surface 600, are sufficiently smooth for a quantum well interface (e.g. between a quantum well layer and a barrier layer) or a heterojunction. The film 600 may be a substrate or template, and the top surface 606 may be sufficiently smooth for subsequent growth of device quality (Al,B,Ga,In)N compound layers 614a (e.g. optoelectronic or transistor device layers) on top surface 606.

The film 600 is typically a direct growth rather than a lateral epitaxial overgrowth. The film 600 may be one or more layers having any thickness, i.e. a thick or thin layer. The film 600 may be thick enough to be a bulk crystal or free standing substrate for example.

A device 616, such as laser, light emitting diode, or transistor, may be fabricated using the film 600. For example, the film 600 may comprise device layers. Or device layers 614a may be deposited on the surface of the film 600. The device

layers 600, 614a might be p-n junction layers, active layers, quantum well layers, barrier layers, or heterojunction layers, for example. The growth 600 may be removed from the substrate 604 to provide a free standing growth or film.

5

#### Possible Modifications and Variations

In addition to the miscut GaN freestanding substrates described above, foreign substrates, such as *m*-plane SiC, ZnO, and  $\gamma$ -LiAlO<sub>2</sub>, can be used as a starting material as well.

10

Although the present invention has been demonstrated using GaN films, AlN, InN or any related alloy can be used as well.

The present invention is not limited to the MOCVD epitaxial growth method described above, but may also use other crystal growth methods, such as HVPE, MBE, etc.

15

In addition, one skilled in this art would recognize that these techniques, processes, materials, etc., would also apply to miscut angles in other directions, such as the *c*-axis direction, with similar results.

#### Advantages and Improvements

20

On-axis *m*-plane GaN epitaxial layers always have pyramid shaped features on their surfaces. By controlling the crystal miscut direction and angle, smooth surfaces can be obtained, and thus high quality device structures can be achieved.

For example, a laser diode with smooth quantum well interfaces would enhance the device's performance. In another example, a smooth interface for heterostructure epi devices, such as high electron mobility transistors (HEMTs) or heterojunction bipolar transistors (HBTs), would reduce carrier scattering and allow higher mobility of two dimensional electron gas (2DEG). Overall, this invention would enhance the performance of any device where active layer flatness is crucial to the device performance.

25

In addition, the enhanced step-flow growth mode via a miscut substrate could suppress defect formation and propagation typically observed in GaN films with a

30

high dopant concentration. Moreover, this would enlarge the growth window of *m*-GaN, which would result in a better yield during manufacture and would also be useful for any kind of lateral epitaxial overgrowth, selective area growth, and nano  
5 structure growths.

### Conclusion

This concludes the description of the preferred embodiment of the present invention. The foregoing description of one or more embodiments of the invention  
10 has been presented for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. It is intended that the scope of the invention be limited not by this detailed description, but rather by the claims appended hereto.

15

## WHAT IS CLAIMED IS:

1. A nonpolar III-nitride film growth on a miscut of a substrate, wherein a  
5 top surface of the film is a nonpolar plane and the miscut is a surface of the substrate  
angled at a miscut angle with respect to a crystallographic plane of the substrate.
2. The film of claim 1, wherein:  
the crystallographic plane is an m-plane;  
10 the nonpolar III-nitride film is m-plane; and  
the miscut angle is towards an a-axis direction and comprises a  $0.15^\circ$  or  
greater miscut angle towards the a-axis direction and a less than  $30^\circ$  miscut angle  
towards the a-axis direction.
- 15 3. The film of claim 1, wherein the miscut angle is  $0.15^\circ$  or greater.
4. The film of claim 1, wherein the top surface is atomically smooth or  
planar.
- 20 5. The film of claim 1, wherein the miscut angle is such that a root mean  
square (RMS) step height of one or more undulations on the top surface, over a length  
of 1000 micrometers, is 50 nm or less.
6. The film of claim 1, wherein the miscut angle is such that a maximum  
25 step height of one or more undulations on the top surface, over a length of 1000  
micrometers is 61 nm or less.
7. The film of claim 6, wherein the undulations comprise faceted  
pyramids.

30



8. The film of claim 1, wherein the crystallographic plane is a nonpolar plane.
- 5 9. The film of claim 1, wherein the miscut angle is sufficiently small such that the film is nonpolar.
- 10 10. The film of claim 1, wherein the miscut angle is such that the top surface, and one or more surfaces of one or more layers deposited on the top surface, are sufficiently smooth for a quantum well interface or a heterojunction interface.
11. The film of claim 1, wherein the film is a substrate or template and the top surface is suitable for subsequent growth of device-quality (Al,B,Ga,In)N layers on the top surface.
- 15 12. A device fabricated using the film of claim 1.
13. A method for growing a nonpolar III-nitride film, comprising:  
(a) growing a nonpolar III-nitride film on a miscut of a substrate, wherein a  
20 top surface of the film is a nonpolar plane and the miscut is a surface of the substrate angled at a miscut angle with respect to a crystallographic plane of the substrate.
14. The method of claim 13, wherein:  
the crystallographic plane is an m-plane;  
25 the nonpolar III-nitride film is m-plane; and  
the miscut angle is towards an a-axis direction and comprises a 0.15° or greater miscut angle towards the a-axis direction and a less than 30° miscut angle towards the a-axis direction.
- 30 15. The method of claim 13, wherein the miscut angle is 0.15° or greater.

16. The method of claim 13, wherein the top surface is atomically smooth or planar.
- 5
17. The method of claim 13, wherein the miscut angle is such that a root mean square (RMS) step height of one or more undulations on the top surface, over a length of 1000 micrometers, is 50 nm or less.
- 10
18. The method of claim 13, wherein the miscut angle is such that a maximum step height of one or more undulations on the top surface, over a length of 1000 micrometers is 61 nm or less.
- 15
19. The method of claim 18, wherein the undulations comprise faceted pyramids.
- 20.
20. The method of claim 13, wherein the crystallographic plane is a nonpolar plane.
- 20
21. The method of claim 13, wherein the miscut angle is sufficiently small such that the film is nonpolar.
- 22.
22. The method of claim 13, wherein the miscut angle is such that the top surface, and one or more surfaces of one or more layers deposited on the top surface, are sufficiently smooth for a quantum well interface or a heterojunction interface.
- 25
23. The method of claim 13, wherein the film is a substrate or template and the top surface is suitable for subsequent growth of device-quality (Al,B,Ga,In)N layers on the top surface.

30

24. A nonpolar III-nitride film fabricated using the method of claim 13.

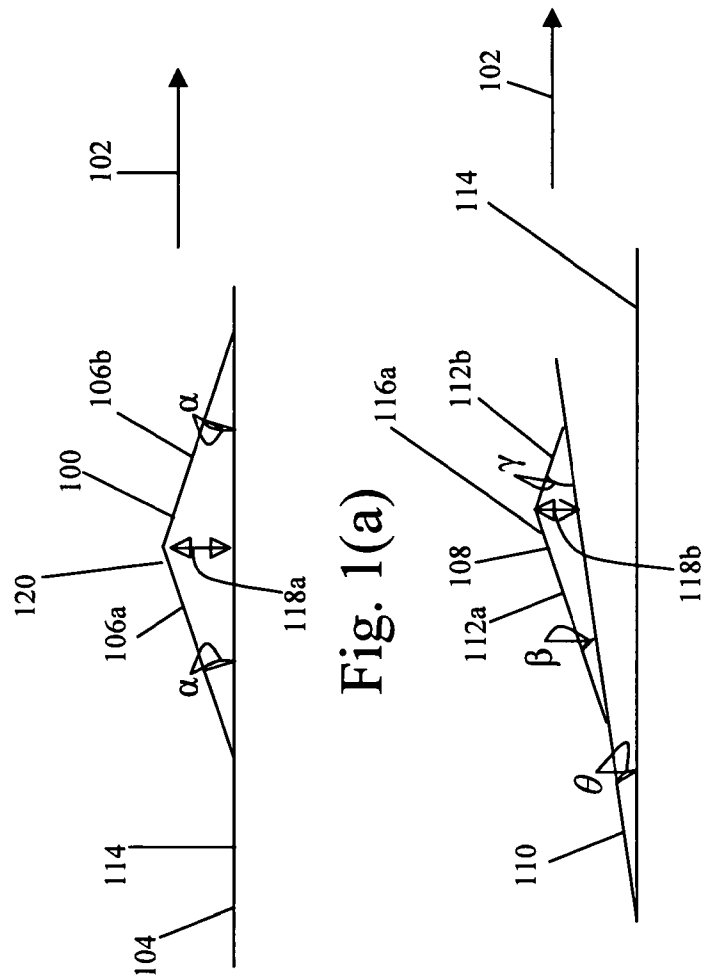


Fig. 1(a)

Fig. 1(b)

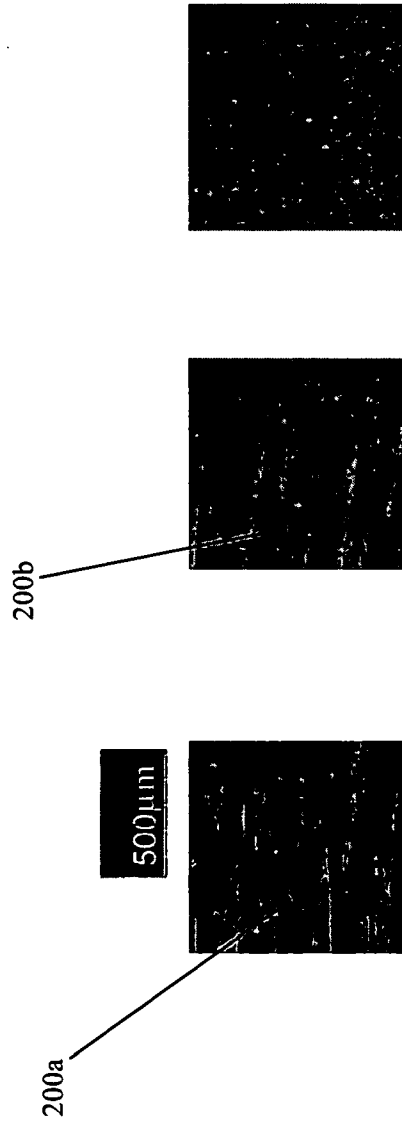


Fig. 2(c)

Fig. 2(b)

Fig. 2(a)

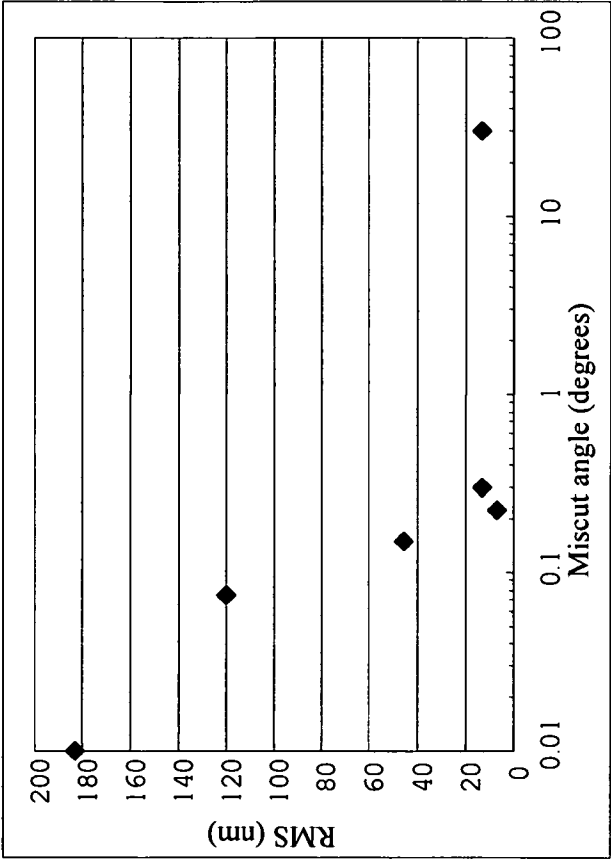


Fig. 3

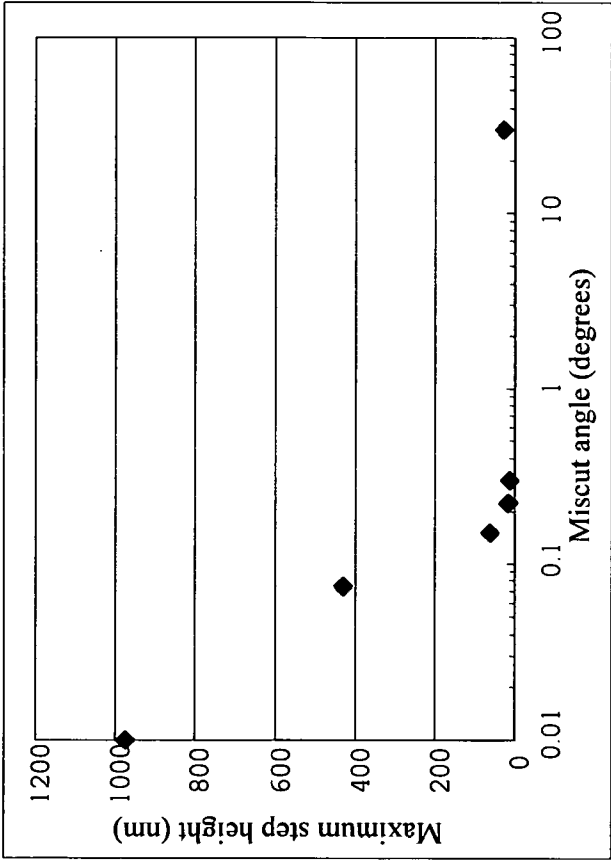


Fig. 4

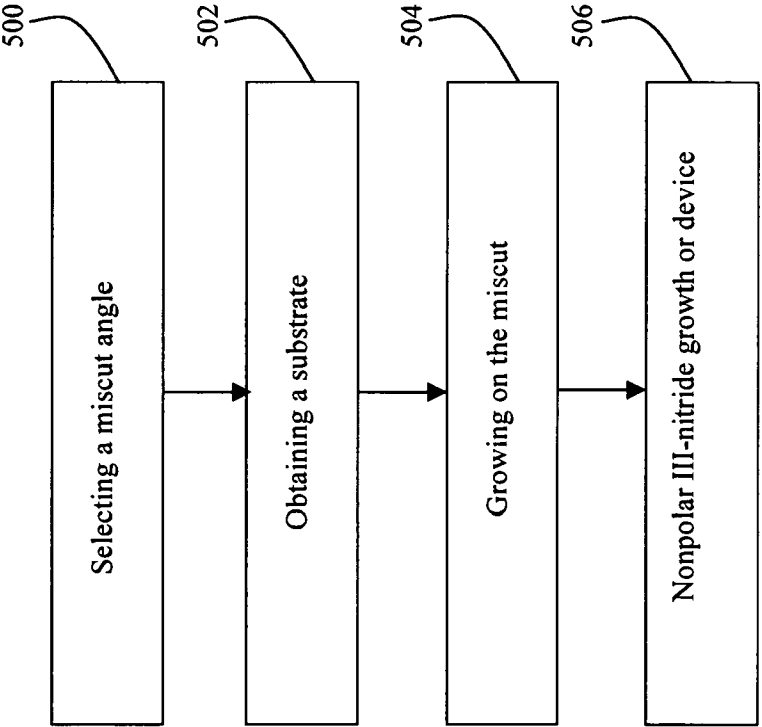


Fig. 5



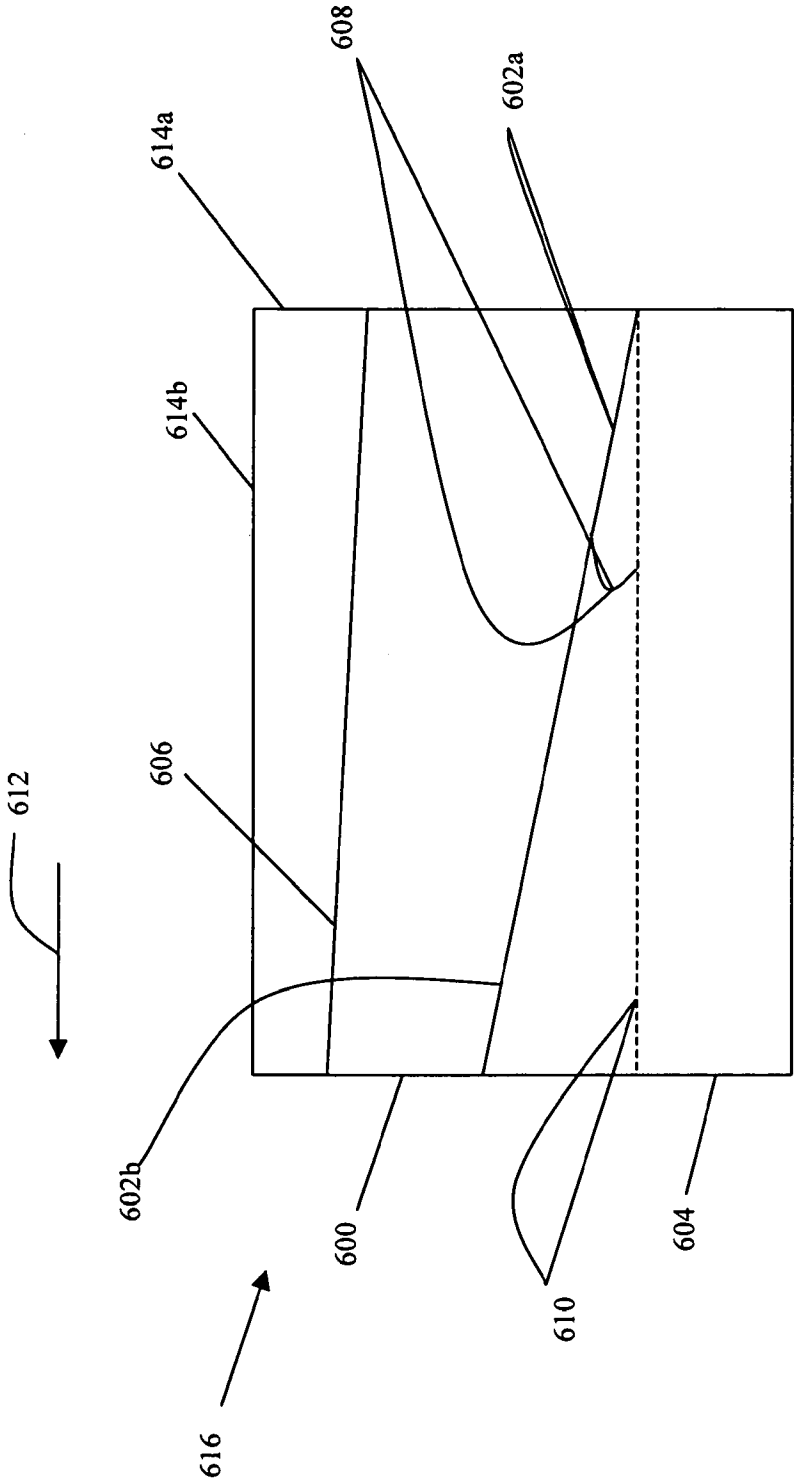


Fig. 6

## INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 08/67149

## A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H01L 21/04, H01L 29/15 (2008.04)

USPC - 438/510; 257/76, 257/E21.11

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8): H01L 21/04, H01L 29/15 (2008.04)

USPC: 438/510; 257/76, 257/E21.11

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

IPC(8): H01L 21/04, H01L 29/15, B32B 3/00, C30B 25/02 (2008.04)

USPC: 438/510; 257/76, 257/E21.11, 428/141, 117/105 (text search)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PubWEST(USPT,PGPB,EPAB,JPAB), Dialog patents, INSPEC, NTIS, PASCAL, Chem Eng BiotchAbst, FreePatentsonline, Google Scholar

Search terms used: terms: III-nitride, film, nonpolar, miscut, substrate, surface, m-plane, axis

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ----- Y	US 2007/0011148 A1 (Chakraborty et al.) 17 May 2007 (17.05.2007), para [0071], [0021], [0022], [0035], [0036]	1, 11-13, 23, 24 ----- 2-10, 14-22
Y	US 6,489,636 B1 (Goetz et al.) 03 December 2002 (03.12.2002), col 4, ln 9-20	2, 3, 4, 5, 6, 7, 8, 9, 10 14, 15, 17, 18, 19, 20, 21-22
Y	US 7,208,393 B2 (Haskell et al.) 24 April 2007 (24.04.2007), col 5, ln 1-5; col 3, ln 42- col 3, ln 60; col 3, ln 42-60; Fig 6, 7	4, 7, 8 10,16, 19, 20, 22
A	US 2005/0208687 A1 (Kasai et al.) 22 September 2005 (22.09.2005), entire document	1-24

☐ Further documents are listed in the continuation of Box C.

\* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&amp;" document member of the same patent family

Date of the actual completion of the international search

05 September 2008 (05.09.2008)

Date of mailing of the international search report

16 SEP 2008

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents  
P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-3201

Authorized officer:

Lee W. Young

PCT Helpdesk: 571-272-4300  
PCT OSP: 571-272-7774